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Optimal Passive Filter Planning in Distribution Networks with Nonlinear Loads and Photovoltaic Systems

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Keywords

«Photovoltaic», «Harmonic phase angle», «Passive filter», «Optimal planning», «Economic analysis».

Abstract

In this paper, the impact of grid-connected photovoltaic (PV) systems on voltage total harmonic distortion (THD_V) in radial distribution systems is investigated. To well present the behavior of PV systems, both amplitude and phase angle of the harmonic current sources are considered in the simulations. Specifically, when the current harmonic phase angle is considered, the photovoltaic and load harmonic may cancel out each other, which results in lower THD_V values. It is also observed form the simulation results that by increasing the PV penetration and nonlinear load demand, THD_V may increase even beyond the allowed range. Therefore, an optimal passive harmonic filter (PHF) planning is also proposed for THD_V mitigation and its effectiveness and applicability is tested and verified under different working conditions. Optimal planning is performed considering a cost objective function which includes PHF cost and benefit of energy loss reduction. According to simulation result, an appropriate passive harmonic filtering could guarantee an acceptable THD_V in radial distribution and reduce energy losses.

Introduction

Due to the environmental and climatic problems of fossil fuels, as well as global warming, the use of renewable energy systems is increasing [1]. Among the emerging technologies, photovoltaic (PV) systems are widely used [2]. However, this power electronic-based technology has given rise to concerns about its contribution to harmonic distortion levels especially in distribution networks, which in turn necessitates harmonic analyses in grid-connected mode [3]-[5]. From the other side, increased penetration of single-phase residential harmonic loads, such as electric vehicles, fluorescent lamps, and single-phase rectifiers is deemed as another potential power quality concern for system operators [6]. High harmonic current distortion can potentially result in equipment de-rating or poor quality of service. However, it must be noted that the total magnitude of harmonic orders injected by residential loads is not necessarily equal to sum of individual magnitudes, due to different harmonic phase angles. As a result, Harmonic impact and the total harmonic distortion (THD_V) may not rise despite the high current harmonic injection. In a similar fashion, when PV systems are connected to the network, depending on the phase angle of load harmonic injection, THD_V maybe be increased or reduced [7].

High THD_V in the network can affect the performance of network equipment, such as transformers, capacitors, etc. It may also cause resonance in the grid. One of the solutions to control the flow of harmonic currents is to use passive harmonic filters (PHFs). Passive filters are divided into series and parallel types. A series filter prevents current harmonic in specific order(s) by means of high impedances, while a parallel filter limits the current harmonic at a certain order by very low impedances. Parallel filters are divided into categories such as single and double tuned, c-type and high pass filters [7]. In this work, single-tuned PHFs are considered for THD_V mitigation mainly due to their simplicity and lower cost. However, to minimize the running cost of the system while meeting constraint on THD_V, optimal setting and sizing of the PHFs are very important. In this regard, many researchers have studied different methods for planning of harmonic filters in distribution networks. As an example, authors of [8]-[10] try to minimize the investment cost, current and voltage THDs throughout the system simultaneously using a multi-objective filter planning optimization model. However, system losses are neglected in this process. In [11], several objective functions are considered as performance indices in the filter-planning problem but optimal placement and sizing is not performed simultaneously. In [12], minimization of power losses and investment cost of PHFs are considered as the objectives of the optimal planning problem. At the same time, voltage limits, number/size of installed PHFs, location of PHFs installation and the THD_V level in all buses are taken into account as the constraints of the mentioned optimization model.

Compared to the reviewed literature, in this paper, joint optimal setting and sizing of the PHFs is investigated in a real distribution system considering minimum system's losses and cost as objectives. A practical framework is developed using digital simulation and electrical network calculation program (DIgSILENT) with an integrated interface to an optimization engine to better match the examined system into the real case and help exploring the system performance more in detail. Unlike the previous studies, both current harmonic magnitude and phase angle are considered in the simulations. To show the effectiveness and applicability of the proposed model, a number of case studies are presented together with key simulation results.

System Description and Modeling

Harmonic injection could be modeled by voltage or current sources. If the THD_V is low, current source could be used to model harmonic injection [13]. In this paper, the current source method has been used to model the PV and load demand harmonic injection, which consists of the current harmonics at different orders.

The case study, as depicted in Fig.1, includes a real LV distribution system located in Yazd province, Iran. The examined system is connected to a 20 kV system through a 20 kV / 0.4 kV transformer while feeding 299 residential loads. In this network, two single-phase PV systems, each with a capacity of 5 kW, are located at the end of a feeder labeled PV1 and PV2 that is connected between phase A and the neutral. The total active load is 141 kW while the total reactive load is 64 kVAr.

In this system, first the effect of current harmonic phase angle modelling is discussed. To this end, the harmonic current magnitude and phase angle of the two PV systems that has been measured in reality by power analyzers during 10 days are set to the corresponding units as shown in Fig. 2. The harmonic current injected in percent by PV to the network depends on PV active power and THD_V of the PV bus. In other words, lower active power and higher THD_V lead to increased percentage of harmonic current. For example, during sunset, the PV active power is low and the THD_V of the network is high due to the residential lighting load. Therefore, the PV current harmonic in percent is very high. It should be noted that the current harmonic in amps during sunset maybe less than the one at noon, because of high active power production. To consider the worst case scenario, one of the biggest harmonic injection magnitude of PVs is used. As can be seen from Fig. 2, because of different grid-interfacing inverter types for the two PV farms, harmonic current is different. Also, the odd and specially 3, 5, and 7 orders are higher. In Fig. 2, the current harmonic contents of the load for all buses are also reported in per unit.

The phase angles of harmonic currents of load, PV1, and PV2 are reported in Fig.3 where two modeling for load current harmonic phase angle are considered to evaluate different impact of current harmonic phase angle on THD_V [7].

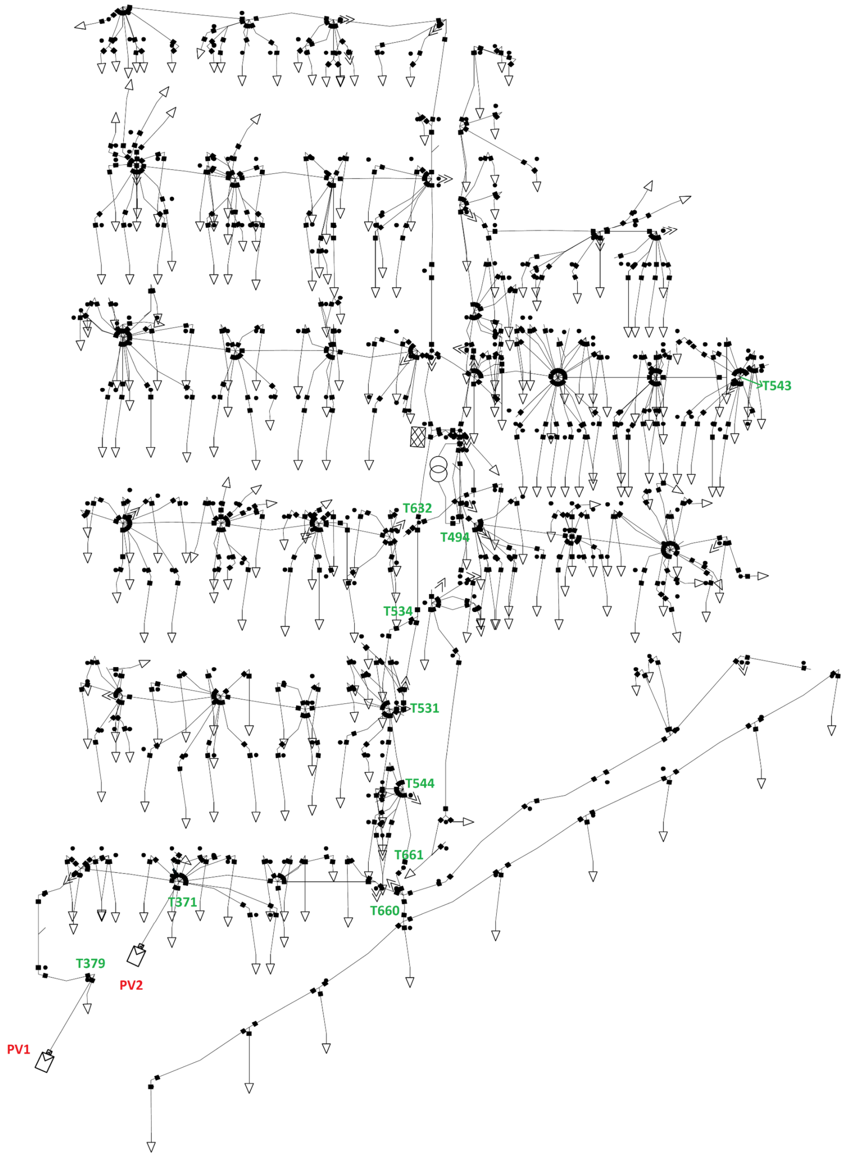

Fig. 1: The examined LV distribution system with nonlinear loads and PV systems

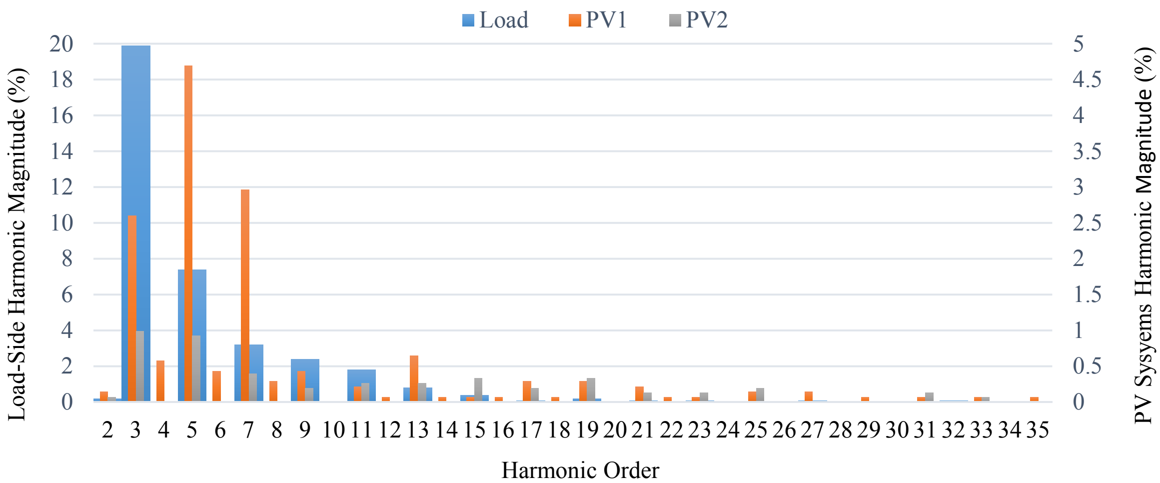

Fig. 2: Harmonic magnitude

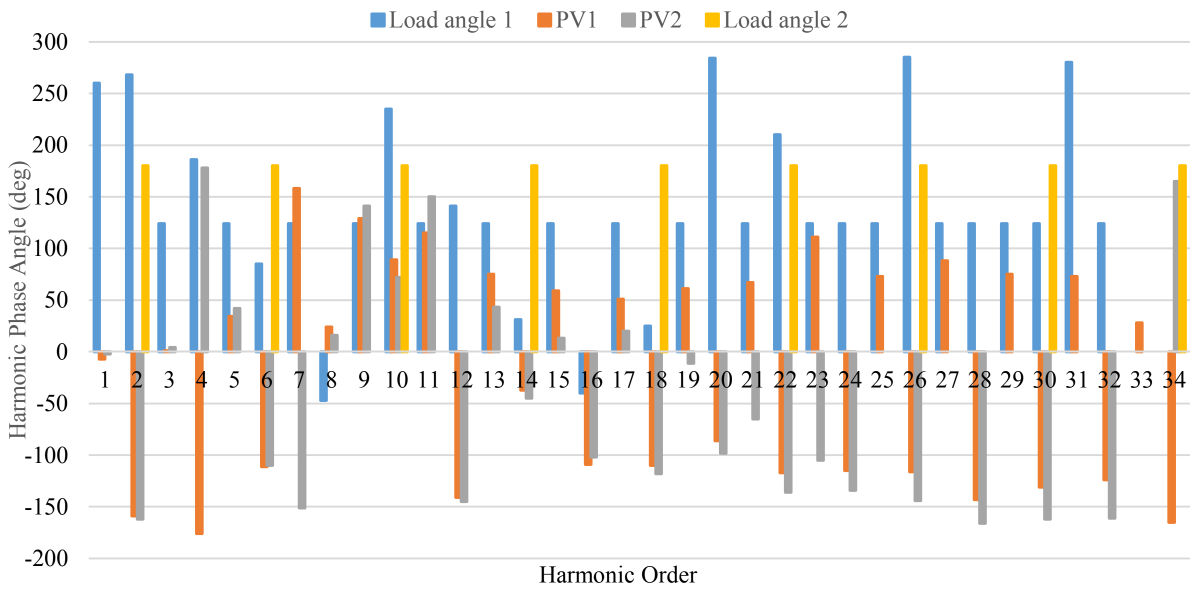

Fig. 3: Harmonic phase angle

Simulation Results

At the first step, impact of current harmonic modeling based on the rated or fundamental current of PV and load on THD_V is evaluated. Thereafter, by assuming disconnected PVs, THD_V is calculated at different buses in the system with and without load harmonic phase angle. Also, by assuming connected PVs, impact of two modeling of load phase angle on THD_V is discussed. The THD_V values of phase A for different cases are reported in Table I.

Table I: THD_V of phase A for different cases

	Current harmonic modeling based on the rated current			Current harmonic modeling based on the fundamental current			
	Without considering load phase angle and disconnected PVs	With load phase angle 1 and disconnected PVs	With load phase angle 1 and connected PVs	With load phase angle 1 and disconnected PVs	With load phase angle 1 and connected PVs	With load phase angle 2 and disconnected PVs	With load phase angle 2 and connected PVs
THD_v at T379	5.9716	4.6065	4.6491	5.5813	5.6674	5.5813	5.4536
THD_v at T524	5.9566	4.5902	4.7062	5.5612	5.7475	5.5612	5.5260
THD_v at T660	5.6501	4.3973	4.5008	5.3237	5.4972	5.3237	5.3451
THD_v at T661	5.6166	4.3740	4.4756	5.2950	5.4660	5.2950	5.3205
THD_v at T544	5.5117	4.3008	4.3968	5.2049	5.3683	5.2049	5.2434
THD_v at T531	5.3243	4.1696	4.2570	5.0439	5.1940	5.0439	5.0918
THD_v at T534	4.9791	3.9282	4.0037	4.7482	4.8786	4.7482	4.7969
THD_v at T552	4.3696	3.4872	3.5427	4.2096	4.3060	4.2096	4.2545
THD_v at T632	3.9242	3.1520	3.1974	3.8035	3.8826	3.8035	3.8435
THD_v at T494	3.9129	3.1438	3.1893	3.7936	3.8727	3.7936	3.8335

As it can be seen in Table I, when current harmonic is calculated based on the rated current or fundamental current values, the resultant THD_V values are different. Also, when PVs are not connected, modeling without including phase angle has higher THD_V than the case where phase angles are taken into account. Therefore, due to considering harmonic phase angle, some harmonic loads can cancel out each other, and thus, the total magnitude of harmonic orders injected by residential loads is not necessarily equal to sum of individual magnitudes. As a result, THD_V is lower in case that phase angles are taken into account. Furthermore, THD_V values increase by connecting PVs to the network when load phase angles are modeled by the first pattern (phase angle 1). On the other hand, when current harmonic phase angle 2 is used, adding PVs can decrease THD_V. To explain how the harmonic phase angle affects the THD_V, the active and reactive injection power of PV1 and PV2 in any orders are shown in Fig. 4.

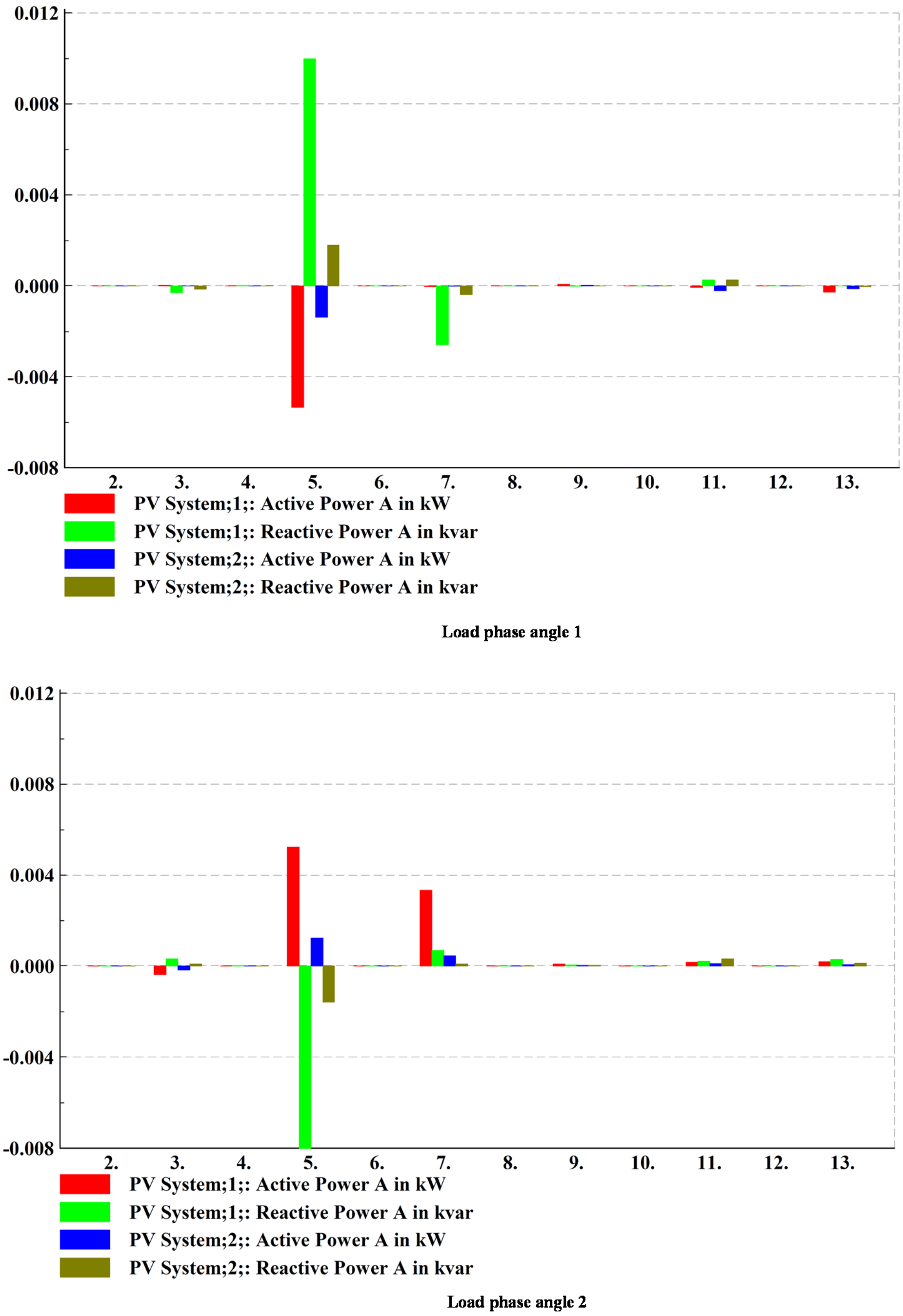

Fig. 4: Injected active and reactive power

In electrical networks with high X/R ratio, the voltage magnitude mainly depends on reactive power. By increasing harmonic order, this ratio gets higher. Therefore, voltage harmonic distortion becomes more dependent on reactive power. As can be seen from Fig. 4, due to higher reactive power production of PVs in case with load phase angle 1 than load phase angle 2, THD_V with load phase angle 1 is higher (i.e. production power is assumed positive).

Considering different scenarios as discussed earlier, it can be easily understood that the THD_V is beyond the limit (>5%) at certain measuring points. Therefore, it is crucial to plan a harmonic filtering action in order to meet the requirements on THD_V. In this regard, an optimal PHF planning is performed to do so. In the proposed optimization problem, the objective function that should be maximized is defined as follows considering allowable THD_V range for all bus as constraint.

$$\text{Maximize F:}\left[\sum_{L=1}^{N}\left((LOSS_{old}\text{-}LOSS_{new})\times PRICE_{mean}\times 24\times 360\times\left(\frac{1+ir}{1+dr}\right)^{L}\right)\text{-}C_{INV}\text{-}(C_{CAP}\times Q_{CAP})\text{-}(C_{IND}\times Q_{IND})\right] \tag{1}$$

s.t.

$$THD_{V,i}\leq THD_{V,\,max}\ \ ;\forall\ i\in N_b \tag{2}$$

where $LOSS_{old}$ and $LOSS_{new}$ are losses before and after PHF planning, respectively, $PRICE_{mean}$ is the average daily energy price. Also, *ir* and *dr* are inflation and discount rates using to calculate the net present value of energy loss reduction. In addition, *N* is the number of operation years. To calculate annual benefit, energy loss reduction is multiplied by 24 and 360. C_{INV} is installation cost of PHF, C_{CAP} is the capacitor cost, Q_{CAP} is capacitor capacity, C_{IND} is the inductor cost, and Q_{IND} is inductor capacity. Similarly, $THD_{V,max}$ denotes the maximum allowed THD_V at any node *i* within the studied network with N_b nodes.

To solve the proposed optimization problem, a metaheuristic approach based on the genetic algorithm (GA) is integrated into the simulation platform, which is run by a DIgSILENT programing language (DPL). The flowchart of the optimal PHF planning with nonlinear loads and PV systems is shown in Fig. 5.

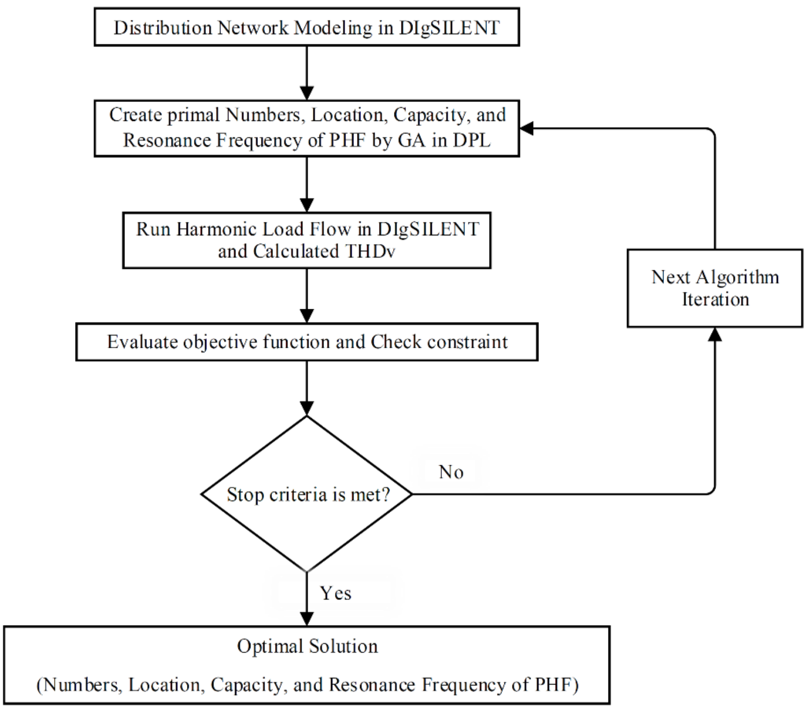

Fig. 5: Optimization flowchart

As can be seen from Fig. 5, at the very first step, the model of the examined distribution network (including line resistance and reactance, active and reactive power and current harmonic magnitude and phase angle of PVs and loads, and distribution transformer) has to be implemented in DIgSILENT. In the next step, primal number, location, capacity, and resonance frequency of PHF is determined by GA through an interfacing DPL file. In the third step, unbalanced harmonic load flow studies are carried out in DIgSILENT to calculate THD_V of all buses and energy loss reduction. Then, if the constraint (2) is met, the value of cost function could be calculated. This process continues until stop criteria is met. As the result, optimal filtering plan in terms of optimal PHF numbers, locations, capacities, and their associated resonance frequencies is provided.

In Table II, the value of $PRICE_{mean}$, number of operation years, and inflation and discount rates [14] are reported. Also, C_{INV} , C_{CAP} , and C_{IND} [15] are shown in this table.

Table II: Economic parameter

$PRICE_{mean}$ (\$/MWh)	63.64
N (year)	20
ir (%)	15
dr (%)	9
C_{INV} (\$/PHF)	12160
C_{CAP} (\$/kVAr)	23
C_{IND} (\$/kVAr)	288

Based on the optimization results, the number, location, capacity, and the harmonic tuning order of the PHF are determined as illustrated in Table III. It should be noted that quality factor of PHF is 50 for nominal frequency [11].

Table III: Sitting and sizing by optimal planning

	Rated reactive power (kVAr)	Harmonic tuning order	Location
PHF1	0.2	5	T371

Simulation results indicate that by using one 0.2-kVAr PHF with odd harmonic tuning order, the THD_V can be easily pushed below the limit. Also, it is observed that this PHF is installed at node where PV system is located.

Table IV shows THD_V for different buses in two different operating conditions namely before and after optimal PHF placement.

Table IV: THD_V of phase A before and after PHF planning

	Current harmonic modeling based on the fundamental current	
	Load phase angle 1 and connected PVs	**Load phase angle 1, connected PVs and installed PHF**
THD_V at T379	5.6674	4.7109
THD_V at T524	5.7475	4.7458
THD_V at T660	5.4972	4.7103
THD_V at T661	5.4660	4.6994
THD_V at T544	5.3683	4.6681
THD_V at T531	5.1940	4.5783
THD_V at T534	4.8786	4.3582
THD_V at T552	4.3060	3.9422
THD_V at T632	3.8826	4.1180
THD_V at T494	3.1893	3.5841

Numerical results of Table IV show that the THD_V values for all nodes are decreased to the allowable limit (5% according to [7]) through optimal setting and sizing of the PHF. This improvement in THD_V

is achieved at a cost of 13545.35$. Moreover, the active energy loss of the system after the filtering action would be around 0.2 kWh averaged over a day.

In Fig. 6 voltage harmonic distortion (HD_V) at T379 before and after planning, is shown. As can be seen, since harmonic tuning order of PHF1 is 5, HD_V in 5 order is decreased. Therefore, THD_V is decreased from 5.6674 to 4.7109.

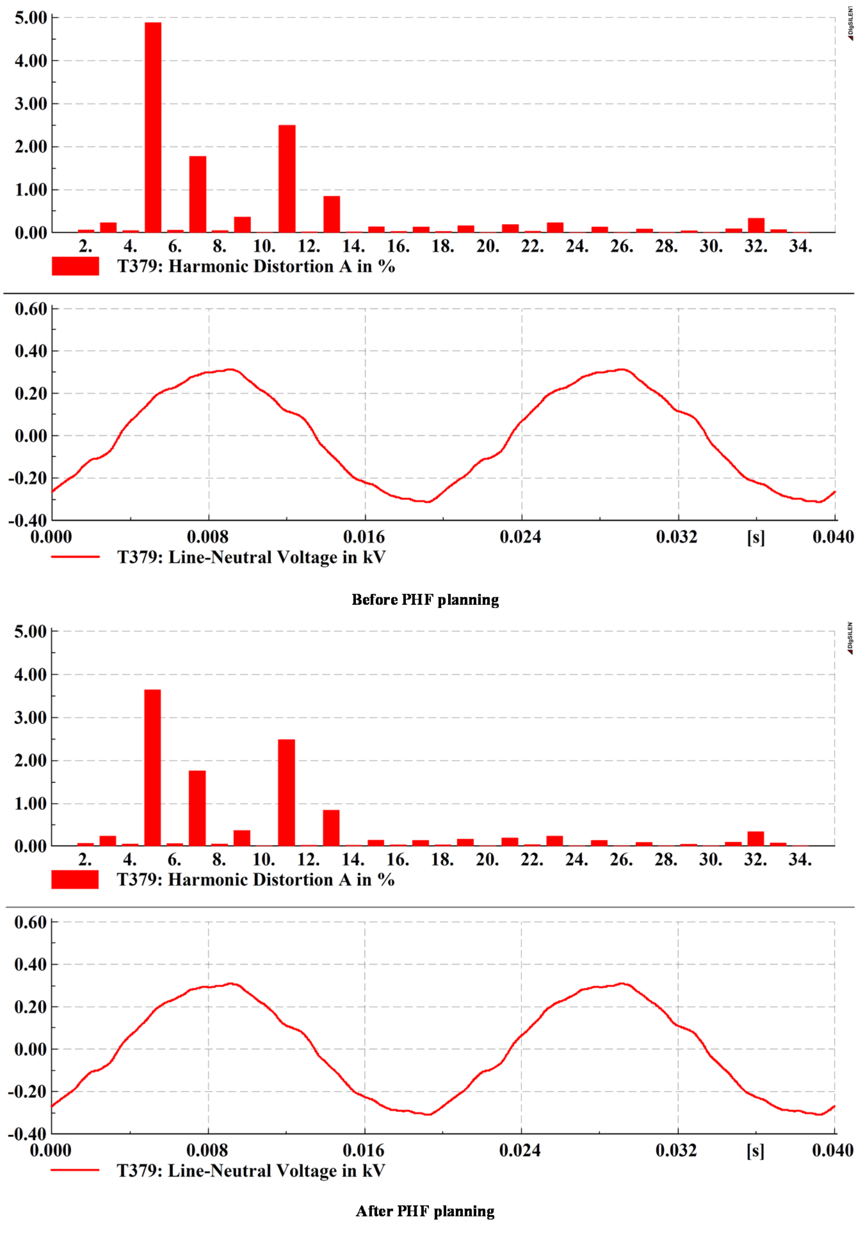

Fig. 6: HD_V before and after PHF planning at T379

Conclusion

It was shown in this paper that the harmonic phase angle injected by the load and/or the PV system could affect the THD_V in different ways. In some operating conditions, the photovoltaic and load harmonics may cancel out each other, which results in lower THD_V values while in some other cases they could augment the harmonic contents of the network. It can be inferred that THD_V depends on reactive power production or consumption of PVs in order 2 to 50. It was also observed form the simulation results that by increasing the nonlinear load demand, THD_V may increase beyond the allowed range. Therefore, an appropriate PHF planning could guarantee an acceptable THD_V level during different operating conditions. In addition, PHF could reduce energy loss over the distribution lines by decreasing current harmonic magnitude.

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